CONTINUOUS FLOW METERING (CFM) ALTERNATIVE SOLUTION TO ALLEVIATE CONGESTION ON INTERSTATE 70 (I-70) EISENHOWER JOHNSON MEMORIAL TUNNEL (EJMT)

Susi Marlina, PhD*
Senior Transportation Analyst
URS
8181 E Tufts Ave. 4th Floor
Denver, CO 80237
Email: susi.marlina@urs.com
Phone: 303-740-2603

Professor Bruce N. Janson, PhD
Department of Civil Engineering
University of Colorado Denver
P.O. Box 173364, Campus Box 113
Denver, CO 80217 – 3364
Email: bruce.janson@ucdenver.edu
Phone: 303-556-2831

Saeed Sobhi, PE
Colorado Department of Transportation
Intelligent Transportation System Manager
425C Corporate Circle Golden, CO 80401
Email: Saeed.Sobhi@state.co.us

*corresponding author
2014

Submitted for presentation at the 2014 Summer Symposium Celebrating 50 Years of Traffic Flow Theory and publication in the Transportation Research Circular, Transportmetrica B, and Journal of Intelligent Transportation System

Abstract

Metering aims to improve traffic flow on the main lanes of a freeway by regulating the inflow to these lanes. While metering is most often implemented at on-ramps to a freeway, it can also be used to regulate the flow of traffic on the main lanes themselves. Although counter-intuitive that regulating flow on the main lanes can also improve overall traffic flow, this can happen in cases where downstream bottlenecks exist. Alternatively, upstream metering may simply be required to prevent excessive queuing at a downstream bottleneck. This paper evaluates two metering techniques applied to the eastbound main lanes of Interstate 70 at the Eisenhower Johnson Memorial Tunnel (EJMT) to potentially improve traffic flow, shorten the queues both east and west of the EJMT, and reduce the need to completely stop traffic at the EJMT. One strategy evaluated is traditional or manual metering in which operations staff stop and start traffic as seen necessary to reduce a downstream queue. The other strategy is called continuous flow metering (CFM), which automatically displays red and green lights at a given cycle length to smooth out the traffic stream as well as reduce downstream queuing. The study results show that CFM did reduce travel times and save person hours of travel in several trial time periods.
INTRODUCTION

Interstate 70 (I-70) provides the only interstate connection from eastern to western Colorado and passes through difficult mountain terrain and physical constraints including the narrow Eisenhower Johnson Memorial Tunnel (EJMT) with only two lanes in each direction. I-70 experiences heavy traffic and subsequently high delays, particularly during the winter time, when travelers are returning from the high country ski areas to the Denver metropolitan area. Interstate 70 is classified as an uninterrupted freeway facility. It frequently serves 50,000 vehicles per day and close to 5,000 vehicles during peak hours. I-70 experiences significant regional and national use by commercial and recreational travel. Weekend travelers returning to Denver from the high country often encounter significant traffic jams, delaying trips by hours because of weekend recreational activities in the mountains.

Figure 1 shows the study area -- a 16-mile stretch of highway running from Silverthorne at the western end (mile post (MP) 205) to Bakerville at the eastern end (MP 221). There are currently three eastbound (EB) lanes from Silverthorne to the lower runaway truck ramp, then two lanes to the US 6 Loveland on-ramp, then three lanes to Hermans Gulch, and then two lanes for the remaining distance to Bakerville. This EB section of highway includes four on-ramps and four off-ramps, none of which lie between Silverthorne and the EB entrance to the EJMT.

The EJMT is the highest highway tunnel in the world (reaching an elevation of 11,000 feet) and is located on I-70 approximately 60 miles west of the Denver metropolitan area. It is a major bottleneck during high volume periods during both on winter and summer weekends. Delays are primarily due to heavy directional volumes, steep grades (7% approaching the EJMT in the eastbound direction), and a long tunnel (1.7 miles). Slower moving trucks on both the up and down grades also contribute to delays, which can be made worse by poor weather conditions and traffic incidents when they occur. In general, a freeway can operate at full capacity when there is good weather, good visibility, no incidents, no work zone activity, and no pavement deterioration serious enough to affect operations.
The basic freeway section analysis of the Highway Capacity Manual (HCM) 2010 (1) provides little guidance for estimating tunnel lane capacities, since the tunnels affect travel speeds quite dramatically. To approximate the capacity of the EJMT, the following specifications were used in the basic freeway analysis of the HCM 2010: 10% heavy vehicles including trucks, buses, and recreational vehicles, 0 interchanges per mile, 60 miles per hour (mph) base free-flow speed (BFFS), and rolling terrain for two lanes in each direction. However, if the lane and shoulder width assumptions reduce the free flow speed (FFS) to below 55 mph, then the HCM does not report a level of service (LOS).

Using these parameters in the HCM basic freeway analysis results in an adjusted capacity of 1800 passenger cars per hour per lane (pc/h/ln), which is roughly the break point between LOS E and F for constrained lane and shoulder width conditions. Although the HCM does not have a capacity adjustment for tunnel effects, the standard capacity reduction for tighter urban streets versus open suburban roadways is 10%. Thus, a 10% reduction in capacity to 1620 pc/h/ln seems about right to account for tunnel effects. This estimate also concurs with the research literature. Levinson et al. (2) estimated the capacity of the Callahan Tunnel in Boston to be between 1600 and 1650 pc/h/ln after installing traffic management improvements. Levinson et al. (2) also cite a New York Port Authority estimate of 1660 pc/h/ln as the maximum theoretical capacity of a tunnel lane. However, observed maximum volumes in New York and New Jersey tunnels suggest a maximum practical capacity of 1350 to 1450 pc/h/ln. Lin et al. (3) estimated the capacity of a tunnel in Taiwan after improvements to be 1300 vehicles per hour per lane (vphpl) in the southbound direction, but only 1150 vphpl in the northbound direction. Koshi et al. (4) observed the capacities of tunnels in Japan under congested conditions to be in the range of 1100 to 1400 pc/h/ln with the average being about 1325 pc/h/ln.

Although these estimates are wide ranging, based on the above investigations, it was estimated that for normal operations, the capacity of the EJMT is roughly 1600 vehicles per hour per lane, or 3200 vehicles per hour (vph) total for the two lanes in each direction.

TRADITIONAL METERING VERSUS CONTINUOUS FLOW METERING

At times, queues of vehicles traveling EB on the east side of the EJMT extend inside the tunnel causing stop and go conditions and restricting access inside the tunnel for emergency response vehicles. To alleviate this congestion and public safety concern, the Colorado Department of Transportation (CDOT) implemented a Continuous Flow Metering (CFM) strategy versus the traditional metering approach. The CFM approach releases the EB traffic on I-70 just prior to entering the EJMT at a rate based on freeway volumes and speeds. This approach differs from the traditional metering approach at the EJMT, which stopped all traffic for up to 20 minutes at a time. The EJMT staff imposed traditional metering at the west entrance to the tunnel to prevent queues in the EB lanes beyond the tunnel from backing up into the tunnel. The shockwave begins in the EB lanes downhill of the tunnel where the geometric characteristics of the highway cause a long queue to form. A study by Zang and Shen (5) found that a lane-drop with low remaining capacity, high travel demand, and a short distance between the merging sign and taper is most likely to produce high oscillations in flow. Furthermore, Laval, et al. (6) found that the evolution of oscillations occurred in freeway segments with no entrances or exits. In this study, oscillation occurs with no entrances or exits, but because of a lane drop, high traffic volumes, traffic incidents, and frequently poor weather conditions.

The traditional metering scheme is to completely stop eastbound traffic at the west entrance and to allow the queue east of the tunnel to dissipate to some point past the US 6/Loveland pass on-
ramp (MP 216.5). At that point, the metered traffic is released. The process is repeated if the EB queue once again nears the tunnel exit. It is not uncommon for traditional metering to be imposed several times on a Sunday of high traffic returning to Denver. The stoppage periods often exceed 10 minutes. After traffic is released, a large platoon of vehicles travels eastbound until it meets the back of the queue.

CFM regulates the flow of traffic into the tunnel similar to ramp metering. The area immediately west of the EJMT entrance was restriped to provide a four-lane metering area similar to a toll plaza approximately 50 feet wide and 500 feet long. An additional lane was striped on either side of the existing travel lanes providing two metering areas for each travel lane as shown in the Figure 2. On an overhead gantry, four signal heads are used to indicate the stop or go for each lane. The metering lanes are released in alternating fashion (lanes 1 and 3, then lanes 2 and 4, etc.), which eliminates the need for vehicles to merge between other vehicles when entering the two tunnel lanes. Although the green release phase is set at two seconds, the frequency of releases could be manually or automatically varied to control the number of vehicles that are released per minute based on queue conditions east and west of the EJMT. After several tests, seven cycle rate plans were developed by FHU (7) for CFM implementation based upon capacity and the condition and movement of the queue east of the EJMT as shown in Table 1. A 170 traffic signal controller is used for implementation due to its capabilities.

**TABLE 1 CFM Cycle Rate Plans**

<table>
<thead>
<tr>
<th>Plan</th>
<th>Green Time per phase (seconds)</th>
<th>Red Time (seconds)</th>
<th>Cycle Rate (seconds)</th>
<th>Capacity (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>10</td>
<td>24</td>
<td>600</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>8</td>
<td>20</td>
<td>720</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>6</td>
<td>16</td>
<td>900</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>5</td>
<td>14</td>
<td>1,030</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
<td>12</td>
<td>1,200</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>1,800</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>2,400</td>
</tr>
</tbody>
</table>
DATA COLLECTED FOR THE METERING SIMULATION

Incidents and recurrent congestion occur almost every weekend and create the need to meter eastbound traffic at the tunnel. Traffic data collected for 14 high traffic days during 2010 and 2011 were reviewed in detail to select a representative day. January 30, 2011 was selected as the case study day for these simulation analyses since (i) that day had the highest eastbound traffic volumes for the 2010-2011 winter season, (ii) incidents occurred and traditional metering was applied eight times between 1:00 PM and 6:00 PM with the longest stop duration being 25 minutes and the shortest stop duration being eight minutes as shown in Figure 3.

Remote Traffic Microwave Sensors (RTMS) collected traffic volumes and speeds in 2-minute bins while the Automatic Traffic Recorder (ATR) in the tunnel collected traffic volumes on an hourly basis. CDOT staff stationed at the EJMT kept a manual log of all traditional metering times and durations.

Figure 4 plots the actual speed data collected on Sunday January 30, 2011. As can be seen by this graph, severe congestion occurred between 12:00 PM and 7:00 PM. The figure shows that the speed dropped at 12:40 PM due to an incident at Hermans Gulch (MP 218.5). To avoid the queue in the tunnel, EJMT staff first metered the traffic from 1:16 PM to 1:41 PM (25 minutes).

MODEL DEVELOPMENT, CALIBRATION AND VALIDATION

Simulation is defined as “a numerical technique for conducting experiments on a digital computer, which may include stochastic characteristics, be microscopic or macroscopic in nature, and involve mathematical models that describe the behavior of a transportation system over extended periods of real time” (8). The VISSIM traffic simulation model was used to simulate and quantify the traffic flow effects of these alternative metering schemes.
Using traffic simulation to replicate the actual conditions is quite challenging, because many variables such as driving behavior and highway characteristics create numerous “what if” scenarios. Developing a realistic model requires significant effort to calibrate and validate the model to replicate the observed conditions. The VISSIM model uses inputs such as vehicle lane assignments, vehicle speeds, percentages of vehicles by type, and pre-timed and/or actuated signal timing (9). Our experience was similar to the finding of Siuhi and Mussa (10) that “the VISSIM default parameters used in trial simulation runs for checking any coding errors showed that the default model parameters were incorrectly emulating the existing traffic flow characteristics”.

Traffic composition in the VISSIM model uses of 97% passenger cars and 3% trucks based on overall EB truck percentages on a typical Sunday afternoon compiled by Hattan and Germeroth (7). Heavy vehicles percentages are often higher during weekday business hours, but less during weekend days with high recreational traffic volumes. Volume balancing was performed during all analysis time periods to ensure that volumes along the I-70 corridor were consistent between interchanges. The balanced mainline volumes were then compared to RTMS counts, additional CDOT counts, and other historical data, such as ramp volumes collected earlier by JF Sato as part of I-70 Mountain Corridor Programmatic Environmental Impact Statement (PEIS). These comparisons were made to determine if traffic patterns were being replicated after the volume balancing procedure was completed. A conservative approach was adopted at locations where balanced volumes were higher than the counts and comparable historical data.
The detailed VISSIM model development for I-70 EJMT network proceeded as follows:

1. Aerial photography from Google Earth was stitched together to create the links and connectors along the corridor. Having the correct scaling is essential for this network.

2. General desired speed range distributions in free flow conditions were used in the model per vehicle type, including passenger cars (50-80 mph with an average of 65 mph), trucks (40-60 mph with an average of 50 mph) and all vehicles through the tunnel (40-50 mph with an average of 45 mph). However, congestion levels and geometric conditions (grades, curves, merging, diverging, etc.) that affect vehicle speed decisions were placed on every entry link and where speed limits change, or on connectors with a different speed limit. Once a vehicle crossed a speed decision area, it will try to maintain that desired speed until it goes over a new speed decision point. The reduced speed zones were coded with a desired speed distribution of plus or minus 5 mph from the initial 10 mph for creating incident.

3. Lane assignments, vehicle inputs, routing decisions, and vehicle compositions were coded to represent existing conditions. Given the scale of this model keeping track of the volume through vehicle input and routing decisions at each junction is very critical to creating a realistic model. Routing decisions are carefully placed so as to not overlap, and so that vehicles cannot accept new routing decisions until they have completed the previous one.

4. Driving behavior parameters, including car following and lane changing parameters, were specified as prescribed by (Wiedeman, 1999) for “freeways”. However, due to unrealistic vehicle behavior resulting from the Wiedeman ’99 parameters, several car following and lane changing parameters (such as headway time (CC1), car following variation (CC2), and the desired safety distance) were changed based on engineering knowledge of the corridor and best practices (11).

5. Each simulation recorded from 11:00 AM to 9:00 PM (10 hours x 3600 seconds = 36,000 seconds) with one-hour seeding time to load the initial traffic demand.

The error checking portion of the model development focused on fixing coding errors before the calibration process began that includes a review of the coded data and a review of the animation. All coded data (geometry, speeds, signal timing data, and traffic volumes) was reviewed. The review of the animation was conducted to determine locations where general coded parameters may have been overlooked. This tuning process involved iterative parameter changing and simulating until simulated speeds closely matched speeds observed in the field. Due to the unrealistic vehicle behavior in comparison to the field observation when using Error checking also involves setting background traffic operation and driver behavior characteristics including gap acceptances, driver aggressiveness, and vehicle characteristics. The default values were adjusted during this process so that the model would accurately reflect observed conditions.

Calibration was performed to get equivalent results between the observed and expected traffic conditions (12). During validation, the VISSIM model output was compared against field data to determine if the VISSIM output was within acceptable levels. The GEH statistic measuring the “goodness of fit” between observed and modeled flows was used for calibration purposes (13):

\[
GEH = \sqrt[2]{(E-V)^2 \over (E+V)/2}
\]

Where, \(E = \) model estimated volume and \(V = \) field count
Calibration and validation were performed in three basic steps: (1) compare bottleneck queue lengths observed in the field and in the simulation, (2) compare field traffic counts to volumes from the simulation, and (3) calibrate system performance to observed speeds and travel times.

Figure 6 shows a comparison of observed counts to simulated volumes at Silverthorne, EJMT West, Hermans Gulch, and Bakerville. When applying a stochastic model, it is not likely that there will be exact volume matches, but the volumes should be relatively close. Figure 7 shows a comparison of observed to simulated speeds at these locations plus a few more where speed data was also collected.

![Figure 6: Comparison of Observed versus Simulated EB Volumes](image)

Table 2 presents VISSIM output as compared to the field data and the resulting GEH statistic. GEH values less than 5 indicate a good fit, and both the bottleneck location and queue length were validated with field observations. It was also confirmed through VISSIM visual animation that the traffic conditions of the model consistently coincided with field observations.

The January 30th incident was modeled in VISSIM by closing both lanes of the two-lane EB for 30 minutes at MP 218.5 starting at 12:34 PM. The queue length used to validate the model was that the queue extended to Loveland Pass (about 1.0 miles) at 12:52 PM as observed in the EJMT staff report. The queue continued to build up to the EJMT West Entrance at 1:03 PM.
FIGURE 7 Comparison of Observed versus Simulated EB Speeds
After the model was calibrated and validated using the actual data, the CFM was then applied. For the traditional metering on January 30, 2011, the average hourly travel time for the entire 16-mile analysis section from Silverthorne to Bakerville exceeded 3 hours at 4:00 PM. Table 3 compares the overall weighted average travel times and the total person-hours of travel time saved for both scenarios. Comparing the simulated queue lengths, the maximum queue length extended seven miles using traditional metering, but only six miles when CFM was modeled.

CONTINUOUS FLOW METERING ON FEBRUARY 24, 2013

Continuous Flow Metering (CFM) was implemented during heavy traffic conditions on Sunday, February 24, 2013 started at 11:50 AM and ended at 6:05 PM. Over the course of 6 hours, the CFM timing as implemented in the field was simulated using Plan 5 for a total of 24 minutes, Plan 6 for a total of 334 minutes, and Plan 7 for a total of 17 minutes. The traditional metering scheme was simulated for nine separate periods to replicate similar conditions when CFM was implemented. Table 4 shows the CFM and traditional metering schedules modeled.

ANALYSIS OF SIMULATION RESULTS

Three measure of effectiveness (MOEs) were selected to compare the traditional metering to CFM. These include total average travel time through the 16-mile study area (from Silverthorne to Bakerville), the total person hours of travel time, and the queue lengths west of the EJMT. As shown in Figure 8, the simulation model estimated a total average travel time of 84 minutes using traditional metering on January 30, 2011, while the proposed CFM metering would have resulted in a total average travel time of 76 minutes for same this day. The simulation resulted in a total average travel time of 62 minutes using CFM on February 24, 2013, while traditional the metering was estimated to result in a total average travel time of 72 minutes for this same day.
TABLE 4  CFM and Traditional Metering Schedules

<table>
<thead>
<tr>
<th>Time Period</th>
<th>CFM Schedule</th>
<th>Traditional Metering</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:50 AM - 2:53 PM</td>
<td>2 sec green time &amp; 2 sec red time (Plan 6) for 63 min</td>
<td>11:50 AM - 12:55 PM</td>
</tr>
<tr>
<td>12:53 PM - 1:10 PM</td>
<td>2 sec green time &amp; 1 sec red time (Plan 7) for 17 min</td>
<td>12:55 PM - 1:40 PM</td>
</tr>
<tr>
<td>1:10 PM - 1:58 PM</td>
<td>2 sec green time &amp; 2 sec red time (Plan 6) for 48 min</td>
<td>1:40 PM - 2:20 PM</td>
</tr>
<tr>
<td>1:58 PM - 2:16 PM</td>
<td>2 sec green time &amp; 4 sec red time (Plan 5) for 18 min</td>
<td>2:20 PM - 3:00 PM</td>
</tr>
<tr>
<td>2:16 PM - 3:01 PM</td>
<td>2 sec green time &amp; 2 sec red time (Plan 6) for 45 min</td>
<td>3:00 PM - 3:27 PM</td>
</tr>
<tr>
<td>3:01 PM - 3:07 PM</td>
<td>2 sec green time &amp; 4 sec red time (Plan 5) for 6 min</td>
<td>3:27 PM - 3:54 PM</td>
</tr>
<tr>
<td>3:07 PM - 6:05 PM</td>
<td>2 sec green time &amp; 2 sec red time (Plan 6) for 178 min</td>
<td>3:54 PM - 4:19 PM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4:19 PM - 4:44 PM</td>
</tr>
<tr>
<td>4:44 PM - 5:09 PM</td>
<td></td>
<td>5 min full stop and 20 min release traffic</td>
</tr>
</tbody>
</table>

As shown in Table 5, the simulation model estimated that CFM would have saved 855 person hours of travel time on January 30, 2011 with an even greater savings of 1,134 person hours on February 24, 2013. These person hours of travel time assume an average vehicle occupancy of 2.6 persons per vehicle.

TABLE 5  Person Hours of Travel Time (TT) Saved

<table>
<thead>
<tr>
<th>Date</th>
<th>Scenarios</th>
<th>TT (hours) of all 16-mile trips (EB)</th>
<th>Person Hours</th>
<th>Person Hours of TT Saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 30, 2011</td>
<td>Traditional Metering</td>
<td>3368</td>
<td>8757</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>CFM</td>
<td>3039</td>
<td>7902</td>
<td>855</td>
</tr>
<tr>
<td>Feb 24, 2013</td>
<td>Traditional Metering</td>
<td>2460</td>
<td>6396</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>CFM</td>
<td>2896</td>
<td>7530</td>
<td>1134</td>
</tr>
</tbody>
</table>

Figure 9 shows an hourly comparison of estimated travel times for the full 16-mile segment from Silverthorne to Bakerville over the 9-hour study period. With traditional metering, travel times ranged significantly from 14 minutes early in the day to a high of 177 minutes (about 3 hours) for vehicles entering this segment during the hour starting at 4:00 PM. The maximum travel time with the CFM strategy was only 120 minutes, which is nearly a full hour less for travelers during this hour. Maximum travel times on February 24, 2013 were estimated to be reached at approximately 3:30 PM, which were 108 minutes using the CFM strategy and 125 minutes if traditional metering were used.
The third MOE examined was the maximum queue length reached on the west side of the tunnel prior to the metering location and propagating down the hill toward Silverthorne. It’s important to reduce this queue to maintain safety and reduce fuel consumption in addition to travel time. As shown in Figure 10, significant queues developed between 1:00 PM and 6:00 PM as a result of using traditional metering in the simulation model, as is observed in the field.

The queue was estimated to reach a maximum length of 9 miles on January 30, 2011 between 3:00 PM and 4:00 PM with traditional metering, but only 7.5 miles with CFM. The queue was estimated to reach a maximum length of 8.1 miles on February 24, 2013 if traditional metering were used, but only 6.0 miles with CFM. These estimates indicate that the longest queues to develop west of the EJMT are consistently shorter with CFM than with traditional metering.

CONCLUSIONS AND LESSONS LEARNED

Simulation can be a very powerful tool for comparing alternative traffic operation plans. Of course, the simulation model requires careful construction and calibration to existing conditions regarding roadway characteristics, vehicle types, driver types, allowable travel speeds, lane changing preferences, and time-of-day variations in entering and exiting traffic volumes. There are many lessons to be learned in the process of developing and implementing a simulation model for a real-world application.
FIGURE 9  Hourly Travel Times Before and After Implementation
Despite the difficulty of proper model specification, once validated to observed data, the model can serve as a very useful tool for comparison purposes. While its estimates may be high or low when compared to observed data depending on the application, the same model applied to the same travel demand subject to operational differences can produce relatively dependable metrics for evaluation.

The objective of this study was specifically to compare the effectiveness of traditional metering versus Continuous Flow Metering (CFM) in serving traffic through a section of I-70 in Colorado that includes the Eisenhower Johnson Memorial Tunnel (EJMT). The simulation results indicate that the implementation of CFM on Sunday, February 24, 2013 improved traffic operations in all aspects evaluated as compared to traditional metering. The following performance measures resulting from the simulation model were better for CFM as compared to traditional metering:

- The average travel time was reduced by 11 minutes, a 15% decrease.
- The highest hourly travel time was reduced by 17 minutes, a 14% decrease.
- The average speed was increased by 22 miles per hour, a 41% increase.
- Person hours traveled was reduced by 1134 hours, a 15% decrease.
- The maximum queue length west of the EJMT was reduced by 2.1 miles, a 26% decrease.

CFM showed similar improvements for these MOE’s when the travel demands of Sunday January 30, 2011 were simulated, a day when traditional metering was in effect.
Other lessons were learned in actual field implementation and monitoring of CFM at this site:

- Utilization of lanes 1 and 4, then lanes 2 and 3 worked better and minimized driver confusion based on the field observations. Heavy vehicles generally stay in the right lane (lane 3).
- It is necessary to estimate the capacity of the tunnel before implementing CFM, to ensure the volume of vehicles allowed to enter the tunnel does not exceed capacity.
- ATR is needed to measure volumes in the tunnel to verify the volume flowing past the metering location. RTMS and field observations are needed to monitor the queue length upstream of the metering location. Travel time runs are needed for actual travel times.
- Using the real-time traveler information or variable message sign (VMS) upstream of the metering area helped the drivers when metering was in effect. The two VMS messages that read “TUNNEL METERING AHEAD” and “USE ALL FOUR LANES” were used.
- The signal heads for CFM include a downward green arrow, a solid yellow and a solid red. The large combined flip signs “STOP HERE ON RED” with diagonal downward arrow and “1 VEHICLE PER GREEN IN EACH LANE” in placed to guide the driver when metering is in effect.

Further research is needed to analyze CFM using different microscopic simulation software (TransModeler or AIMSUN for example) in different settings with different volumes. Although this high altitude crossing of the Continental Divide is unique to Colorado, the usefulness of CFM in other settings is expected to be seen.

ACKNOWLEDGMENTS

The author would like to thank a number of people who have contributed to this study, both directly and indirectly. Dave Hattan (Felsburg Holt & Ullevig), Scott Thomas and Bart Przybyl (Apex Design), Will Johnson (Parsons Brinckerhoff), and Kathie Haire (HDR Inc), who provided valuable guidance and data, supportive assistance, and helpful discussions on this study, and Travis Boone and Mark Schaefer (URS) who provided travel support to present this paper.

REFERENCES